Georgia Tech

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School of Aerospace Engineering

# Tests and Interpretation of Small Fatigue Crack Growth in Metallic Rotorcraft Structures with Emphasis on the Statistical Characteristics

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*Grant NGT 2-52274*

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# Participants

## Faculty

- ***George A. Kardomateas*** *(Professor)*
- ***Robert L. Carlson*** *(Professor Emeritus)*

## GRA's

- ***Marcus Cappelli*** *(Presidents Scholar, PhD student)*
- ***Wendy Hynes*** *(Senior Engineer, Lockheed Martin, M.Sc. student)*

## Undergraduate Honors Program Assistants

- ***Christopher Neglia***

# Topics

- *Summary of Problem*
  - *Bi- Modal cluster cracking*
- *Previous Research*
  - *Scatter in small fatigue crack growth from micro-notches.*
- *Current Research*
  - *Data*
  - *Summary of issues involved in small fatigue crack growth from smooth surfaces.*
  - *Analysis*

# Background

- ***Features of small crack growth***
  - ***Growth-arrest***
  - ***Coalescence of microcracks***
  - ***Growth at smaller SIFs and at faster rates than equivalent long cracks***
  - ***Scatter significantly greater than that for long cracks***

# Causes of Scatter

- *Each small crack front will encounter randomly oriented microstructure and thus have a unique growth pattern.*

- *Different material forms will have varying grain profiles.*

  *Ex. Grains in stock rod will be thin and elongated while those in plate are characterized by three dimensions; longitudinal, transverse and short transverse.*

- *Randomly arranged crack cluster neighborhoods affect growth through shielding and coalescence.*

# Smooth Surface Current Research

- *On smooth surfaces the onset of cracking occurs in randomly arranged clusters described as micro-multi-site cracking.*
- *Many cracks will arrest (effectively non-propagating cracks), secondary.*
- *Propagating (primary) cracks are those that continue to grow, possibly through crack coalescence and can ultimately lead to failure.*
- *Primary cracks are influenced by the shielding effects of the network of nearby secondary cracks which create a unique environment for growth.*

# Bi-Modal Crack Distributions

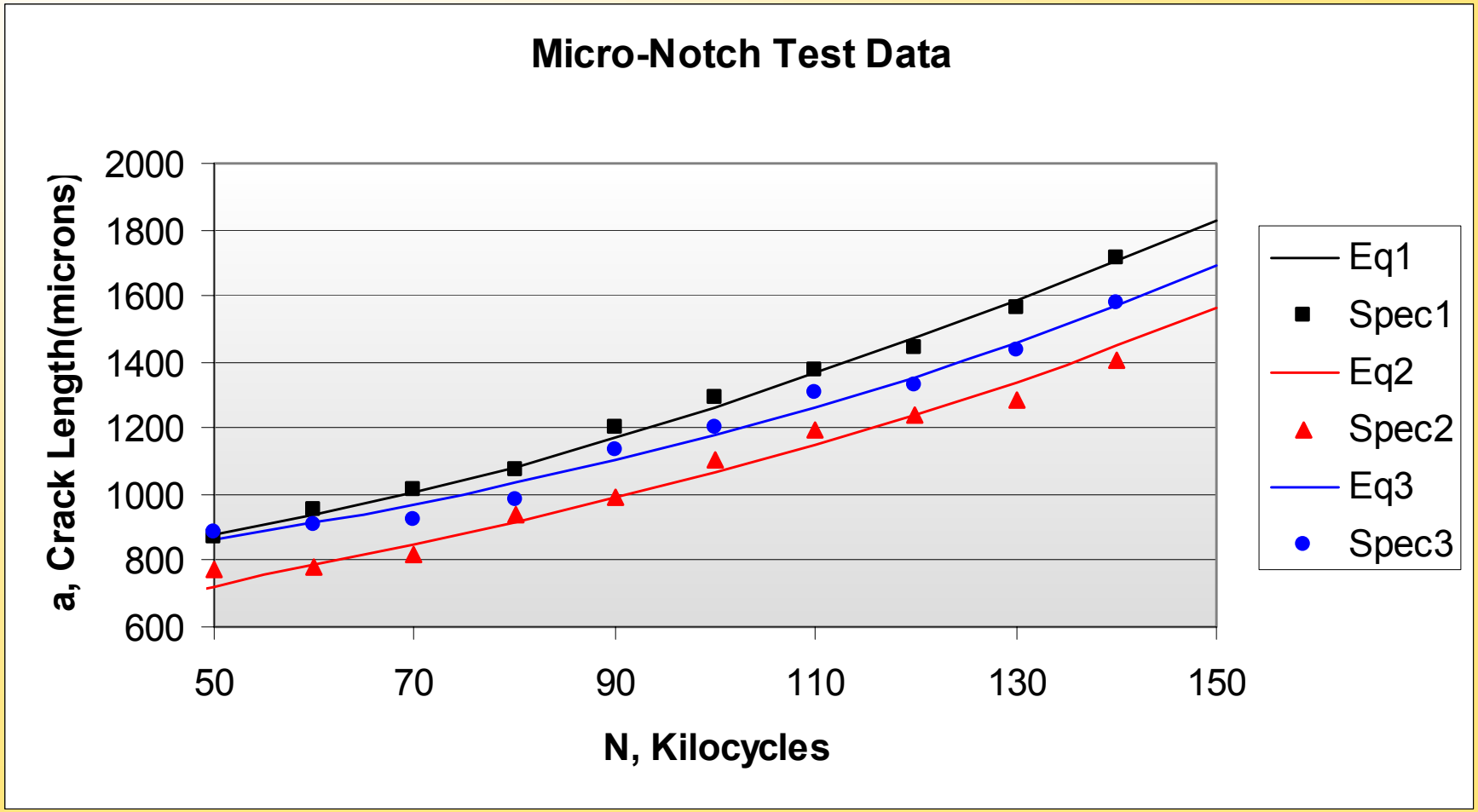
- *Small Crack distributions are bi-modal: Both primary and non-propagating cracks have separate distributions.*
- *First noticed by Swain who termed Valid and Invalid cracks while looking for which cracks to include in studies.*
- *Distributions cannot be separated in early stages of loading.*
  - *Measurements are started once cracks are of a detectable size.*
  - *Tests are stopped at regular intervals and cracks/clusters are measured and recorded.*
  - *Tests are run until failure.*
  - *Based on long crack data the distributions can be separated.*

# Micro-Notches Past Research

- *Test Setup*
  - *Alloy: 6061-T651 (rod form)*
  - *Grain size: Transverse -200 microns, Longitudinal - 350 microns*
  - *Properties: 0.2% offset yield stress – 283 MPA, ultimate strength – 293 MPA*
  - *Test specimen: Square cross-section 150 micron notch corner edge*
  - *Loading condition: Bending about a cross section diagonal*
  - *Maximum stress of 0.8 yield stress on corner edge*
  - *Loading frequency: 10Hz*

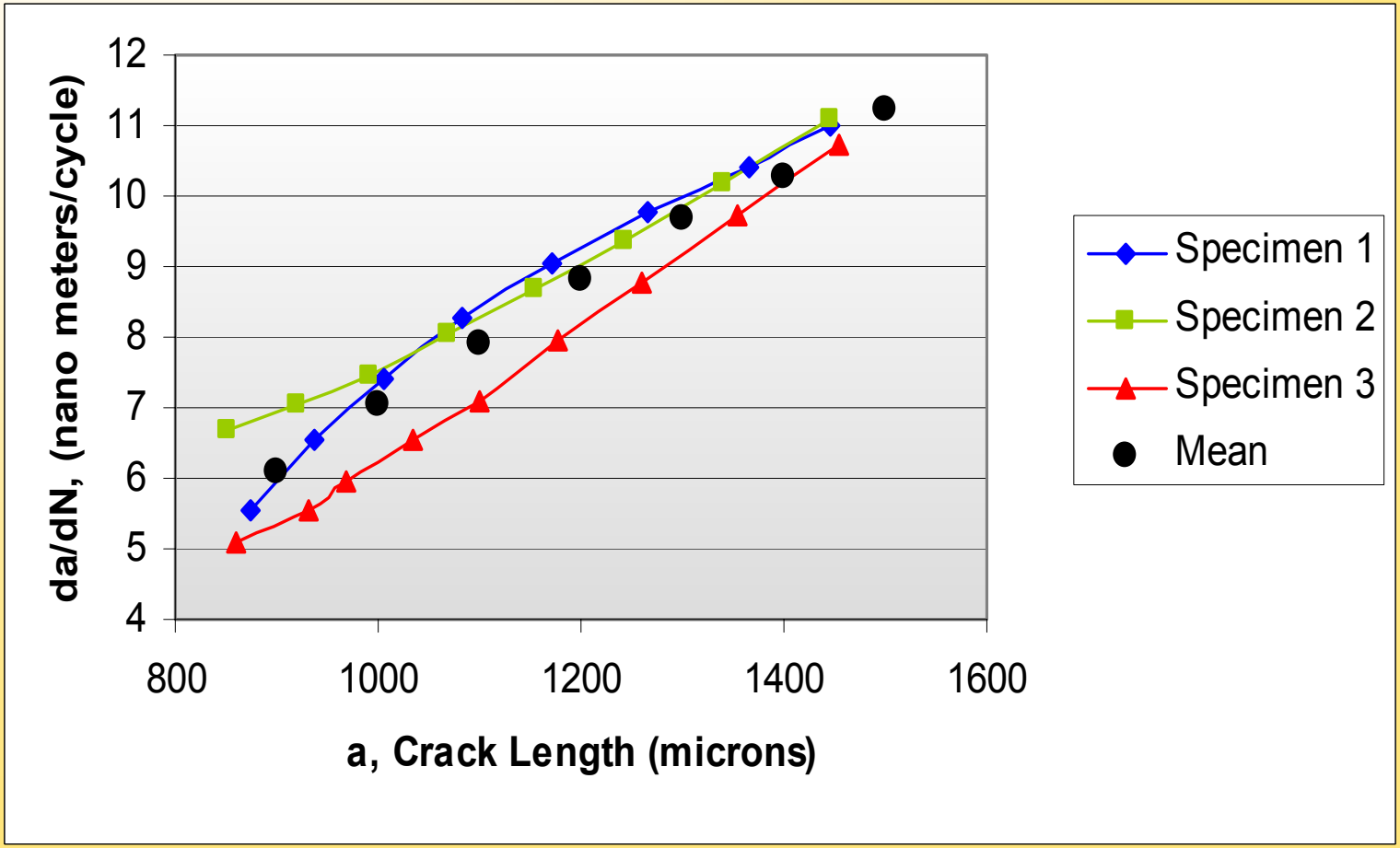
# Test Data

- *Cubic Regression Analysis Performed on Data*



# Regression Analysis

- *da/dN computed by differentiating resulting equations*



# Trends in Standard Deviation

- *Behavior of S.D. of crack growth rates can be represented by exponential function of the form:*

$$S = Ce^{B\Phi(a)}$$

- *a = crack length, C,B = Constants*
- *Nonlinear regression analysis provides the following:*

$$S = 0.81e^{\left[-2.299\cdot10^{-6}(a-800)^2\right]}$$

# Grain Intersection Analysis

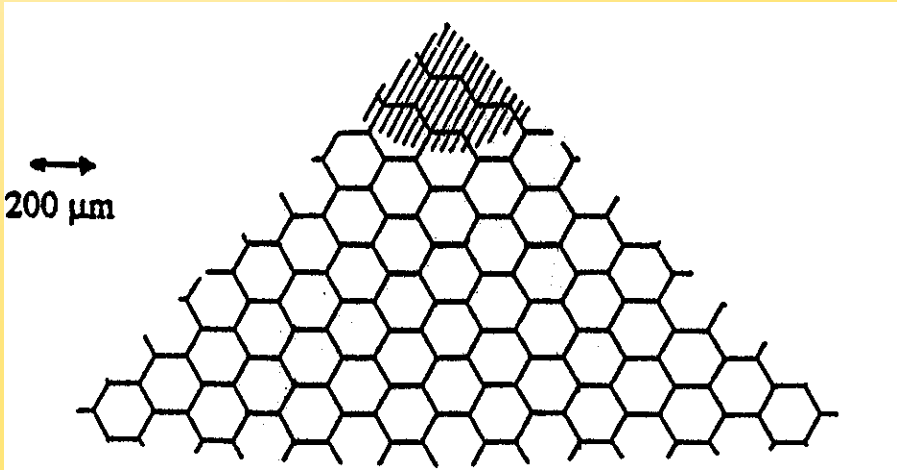
- *Corner Crack fronts assumed to grow with quarter circular crack fronts.*

$$n = \frac{1}{2}\pi\left(\frac{a}{d}\right)$$

- *n = number of grains intersected by crack front*

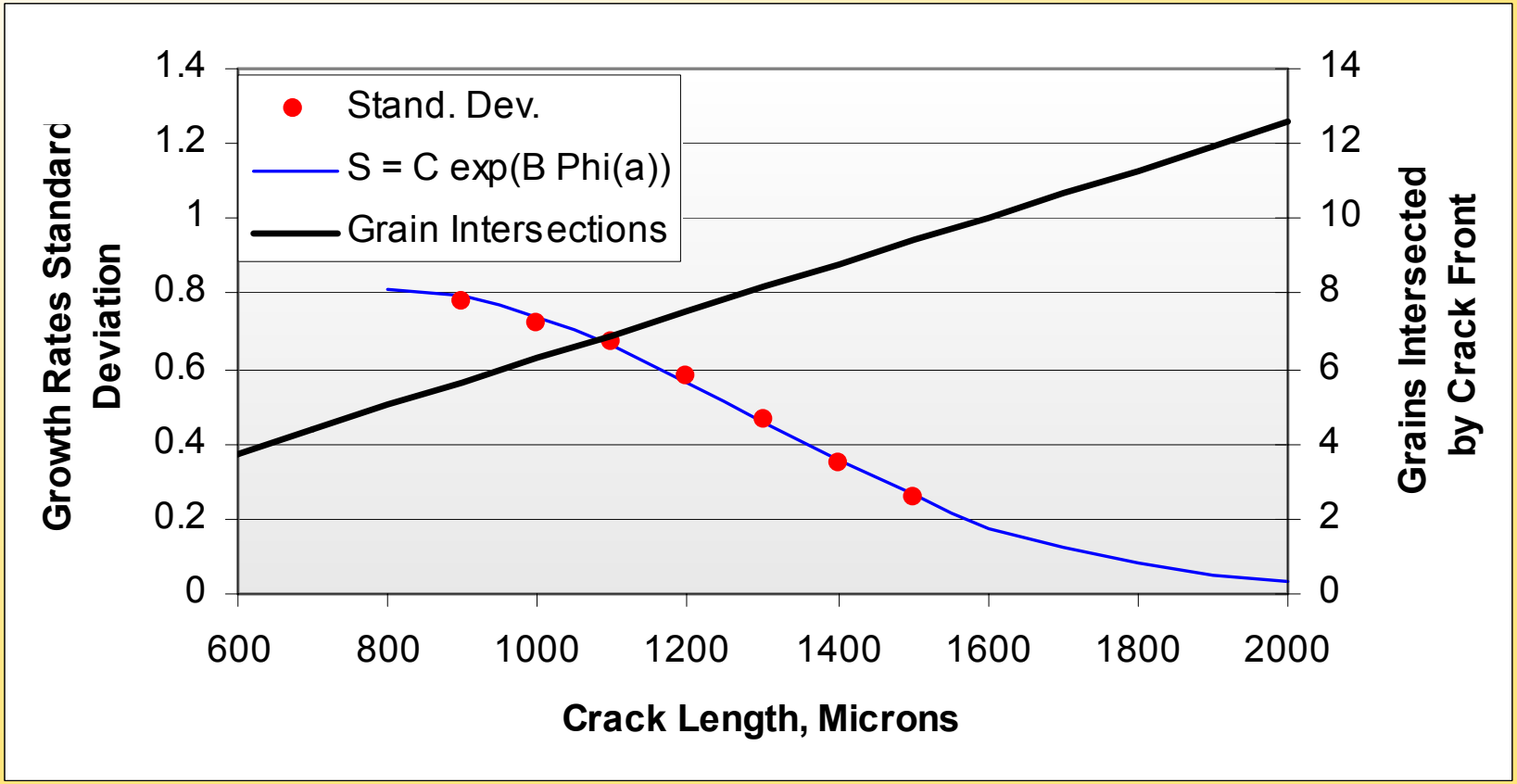
  *a = Crack depth*

  *d = Mean grain diameter*



# S.D. and Grain Intersection Relations

- *Grain Intersections and Standard Deviation Vs. Crack Length*



# Grain Intersection Relations

- *Number of grains intersected by crack front is a linear function of the crack length.*

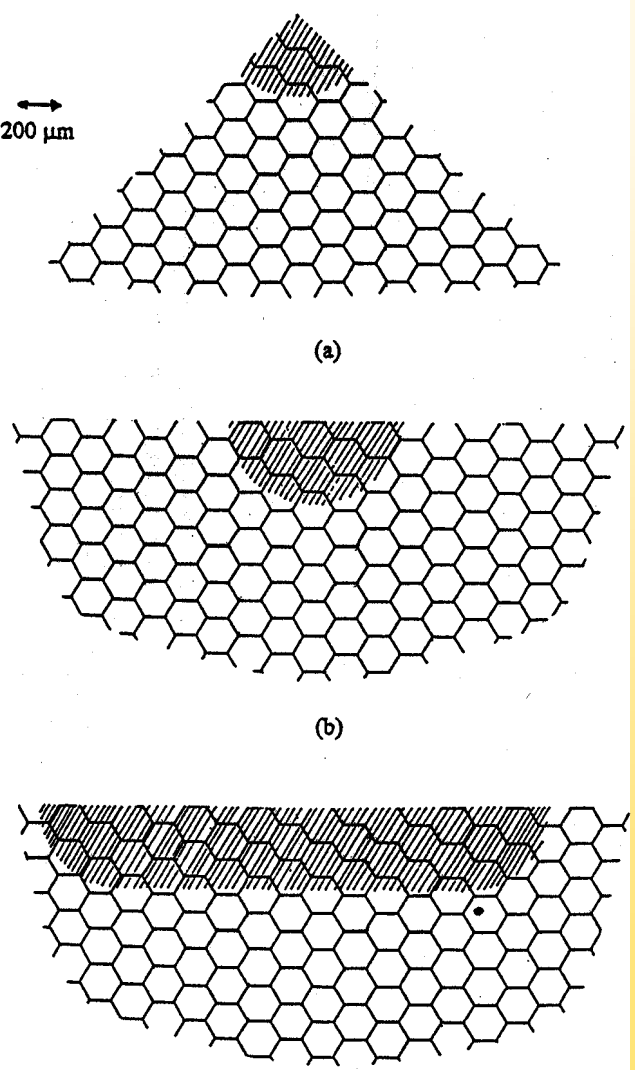
- *S.D. can therefore be expressed as a function of number of intersections:*

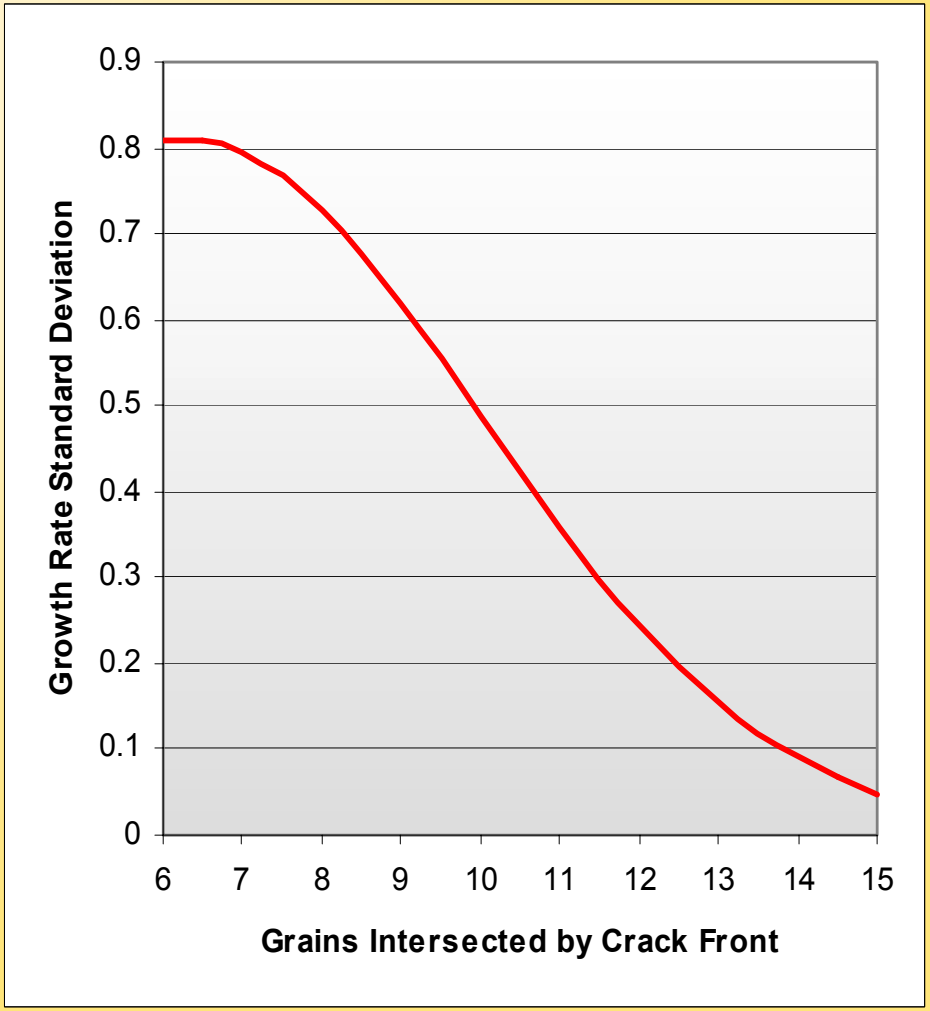
$$S = Ce^{B\Theta(n)}$$

- *Applications to multiple crack shapes*
  - *Ex. Thumbnail cracks intersect twice as many grains as similar depth corner cracks.*

# Grain Intersection Relations

- *S.D. in Growth Rate vs. Grain Intersections*



# Distribution Separation

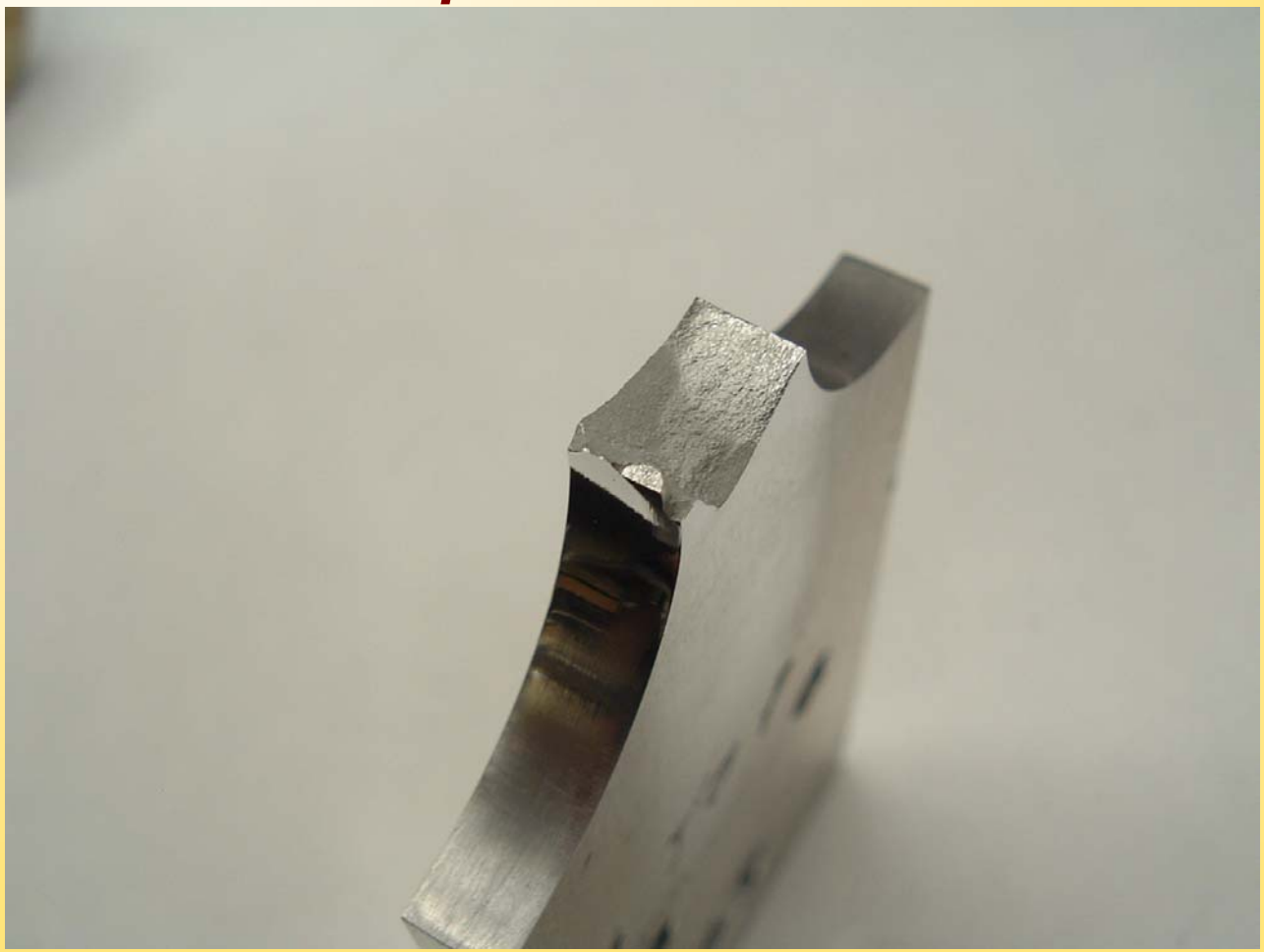
- *Primary cracks are those that have reached long crack size by failure.*
- *Cracks assumed to be semi-circular and be long after 14 grain intersections.*

$$n = \frac{1}{2}\pi\left(\frac{a}{d}\right), \; d = .00145in\,(long./short\ tran.)$$

- *Semi-circular assumption backed up by failed specimen observations.*
- *Borderline cracks are separated by observing crack growth rates.*

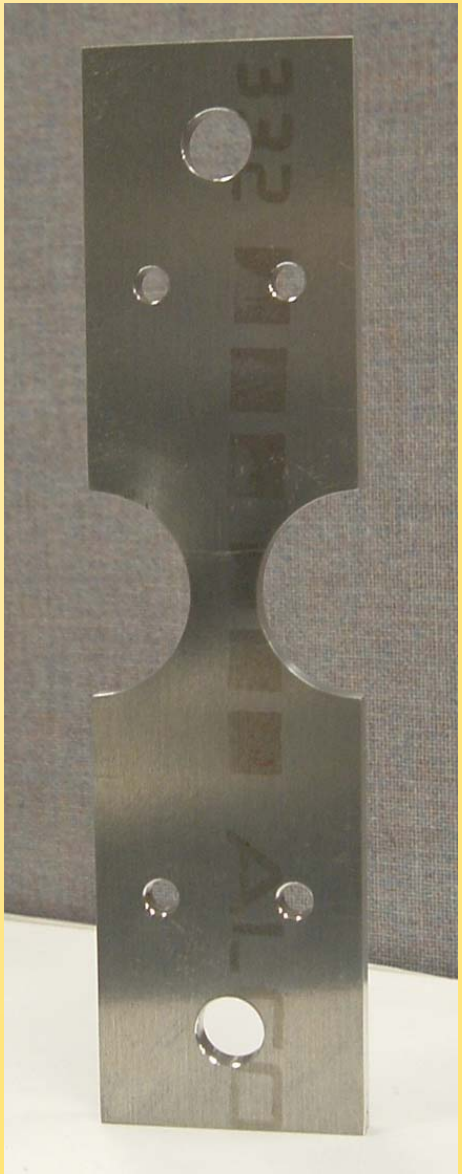
# Distribution Separation

- *Failed specimens often reveal additional cracks that did not lead to specimen failure.*



# Test Procedure

- *Sinusoidal Loading*
- *Loading Frequency: 20 Hz*
- *R = .1, Max Load 5000 Lbs*
- *Max Load approx. 75% $\sigma_{yield}$*
- *Measurements taken on Questar Telemicroscope.*

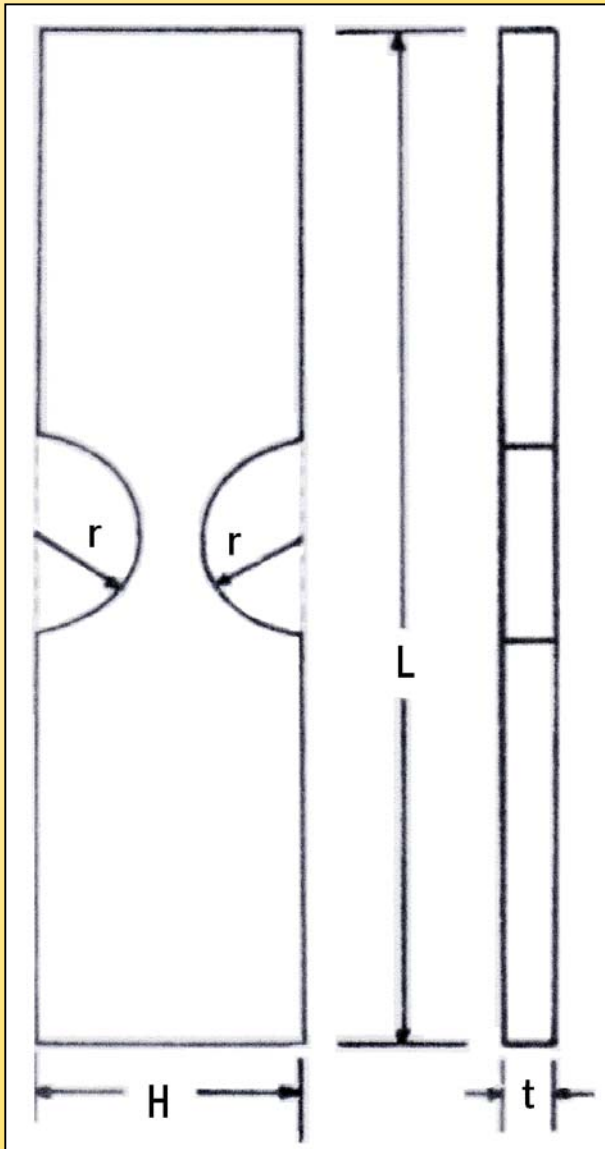


# Test Specimen

- $L = 8$ in, $H = 2$ in
- $t = 0.25$ in, $r = 0.75$ in

- *SCF* = 1.2 *(over ligament stress)*

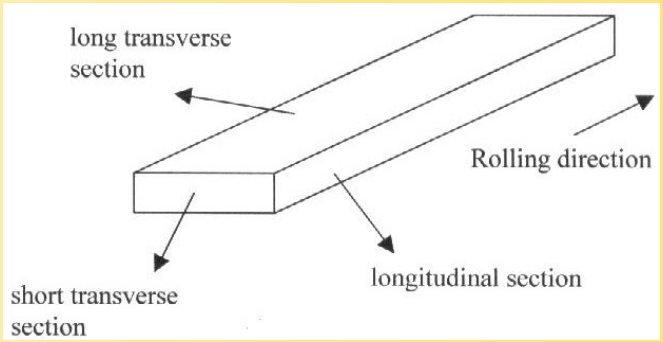
- *Mid-Section Polished with:*
  - *Three abrasive papers*
    - *240, 320, 600*
  - *Three Diamond Pastes*
    - *15, 6, 1μ (applied with low nap cloth)*



# Material Properties

## Aluminum 7075-T7351

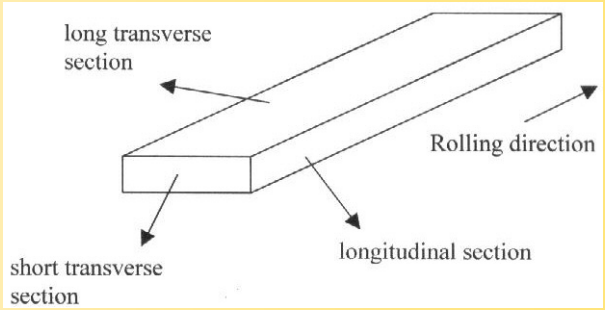
- *Material Properties:*
  - *Mean $\sigma_{yield}$= 64.0 ksi*
  - *Mean $\sigma_{Ult}$= 75.3 ksi*

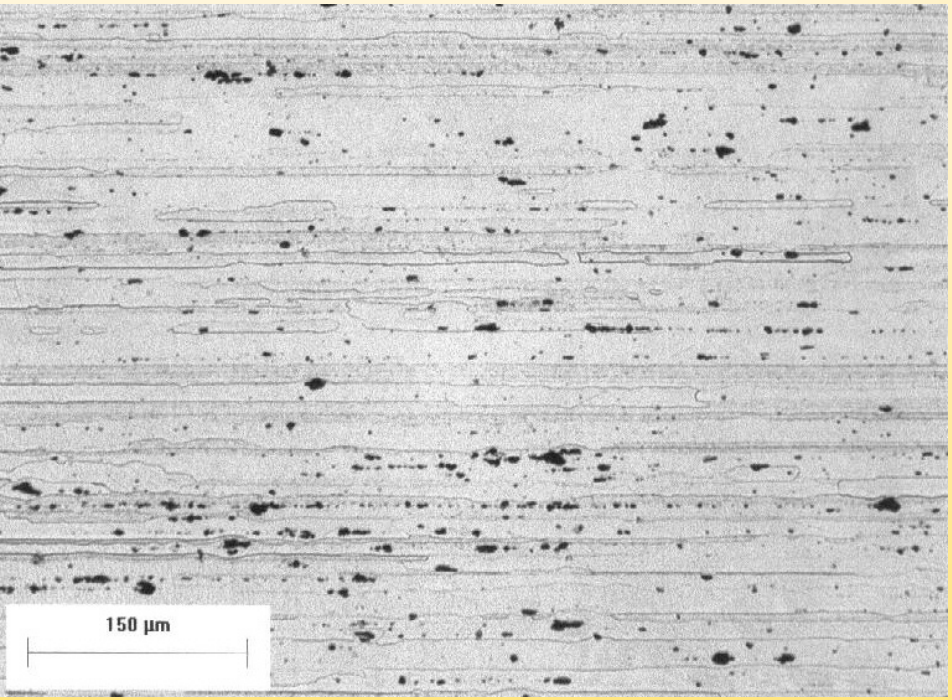


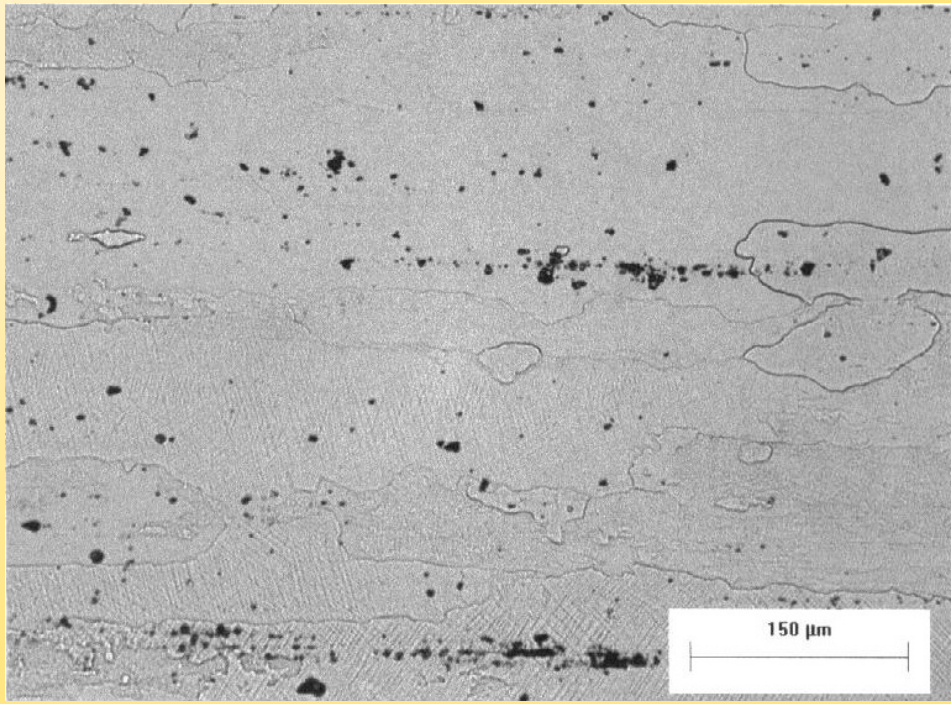

- *1/4 inch plate material with pancake grain structure.*
- *Mean linear intercept grain dimensions:*
  - *58.8 microns (Longitudinal)*
  - *76.1 microns (Transverse)*
  - *15.0 microns (Short Transverse)*

# Material Properties

- *Sample of material etched with Kellers reagent*




*Longitudinal*

*Short Transverse*

# Raw Data Sample

*Stepped Crack, Coalescence, additional data*

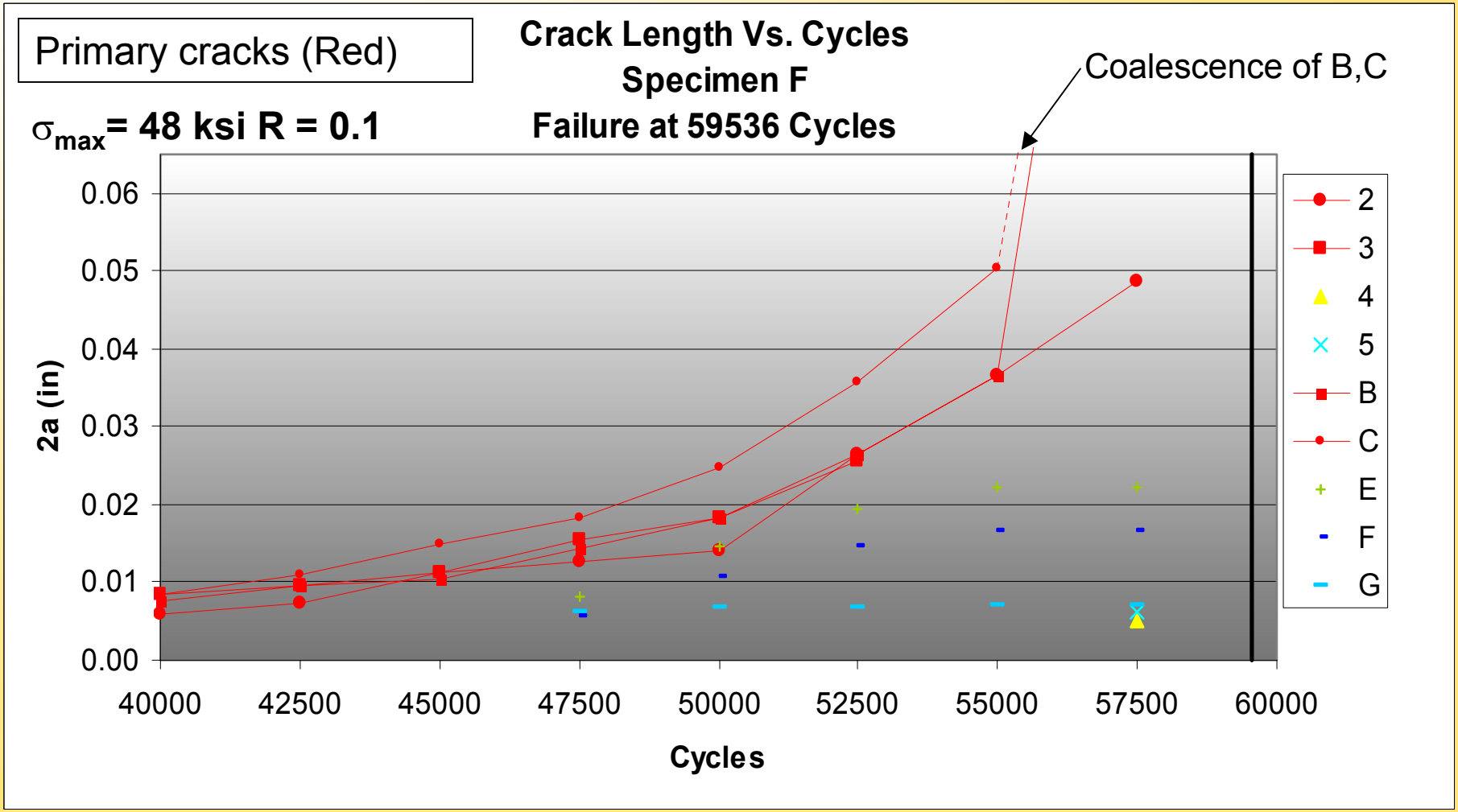
| Specimen C | 60294 | Cycles to Failure | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cycle Count | | 40000 | 42500 | 45000 | 47500 | 50000 | 52500 | 55000 | 57500 | 60000 |
| | | | | Distribution: | Primary | | | | | |
| Crack A | Side 2 | | | | | | | | | |
| y | | | -0.04985 | -0.04955 | -0.10320 | -0.10190 | -0.10630 | -0.10640 | -0.10470 | -0.10285 |
| X1 | | | 0.15770 | 0.15445 | 0.15375 | 0.15510 | 0.14985 | 0.14445 | 0.14735 | 0.13725 |
| X2 | | | 0.16260 | 0.16305 | 0.16405 | 0.16760 | 0.16605 | 0.17120 | 0.18615 | 0.19745 |
| 2a | | | 0.00490 | 0.00860 | 0.01030 | 0.01250 | 0.01620 | 0.02675 | 0.03880 | 0.06020 |
| Growth Rate | | | 0.00000148 | 0.00000108 | 7.8E-07 | 0.00000118 | 0.00000285 | 0.00000452 | 0.00000669 | 8.56E-06 |
| | | | | | | | | | | |
| | | | | Distribution: | Primary | | | | | |
| Crack B | Side 2 | | | | | | | | | |
| y | | | | | 0.06965 | 0.07140 | 0.06665 | 0.06680 | 0.06780 | 0.06890 |
| X1 | | | | | 0.09030 | 0.08875 | 0.08415 | 0.07900 | 0.08765 | 0.08430 |
| X2 | | | | | 0.09595 | 0.09845 | 0.09530 | 0.09460 | 0.10455 | 0.10775 |
| 2a | | | | | 0.00565 | 0.00970 | 0.01115 | 0.01560 | 0.01690 | 0.02345 |
| Growth Rate | | | | | 0.00000162 | 0.0000011 | 0.00000118 | 0.00000115 | 0.00000157 | 0.00000262 |
| | | | | | | | | | | |
| | | | | Distribution: | Secondary | | | | | |
| Crack C | Side 2 | | | | | | | | | |
| y | | | | | | 0.00620 | 0.00165 | 0.00135 | 0.00285 | 0.00415 |
| X1 | | | | | | 0.07810 | 0.07415 | 0.07065 | 0.07675 | 0.07655 |
| X2 | | | | | | 0.08470 | 0.08250 | 0.08100 | 0.09120 | 0.09240 |
| 2a | | | | | | 0.00660 | 0.00835 | 0.01035 | 0.01445 | 0.01585 |
| Growth Rate | | | | | | 7E-07 | 7.5E-07 | 0.00000122 | 0.0000011 | 5.6E-07 |
| | | | | | | | | | | |
| | | | | Distribution: | Secondary | | | | | |
| Crack G | Side 2 | | | | | | | | | |
| y | | | | | | | -0.10845 | | | |
| X1 | | | | | | | 0.16805 | | | |
| X2 | | | | | | | 0.17285 | | | |
| 2a | | | | | | | 0.00480 | | | |
| Growth Rate | | | | | | | | | | |

*Location Coordinates*

*Coalesced with A*

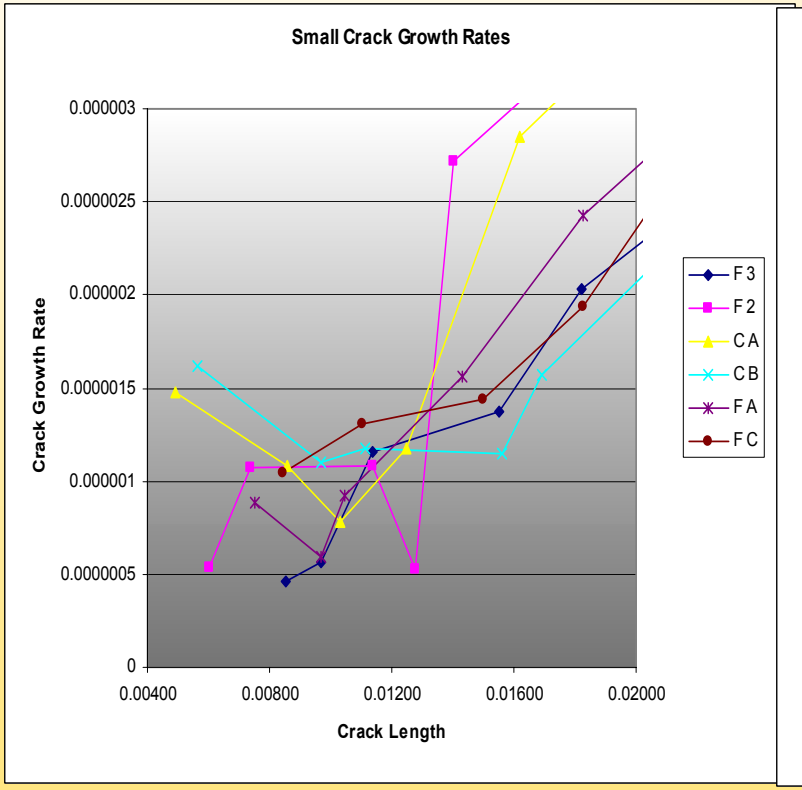
# Crack Measurement Data

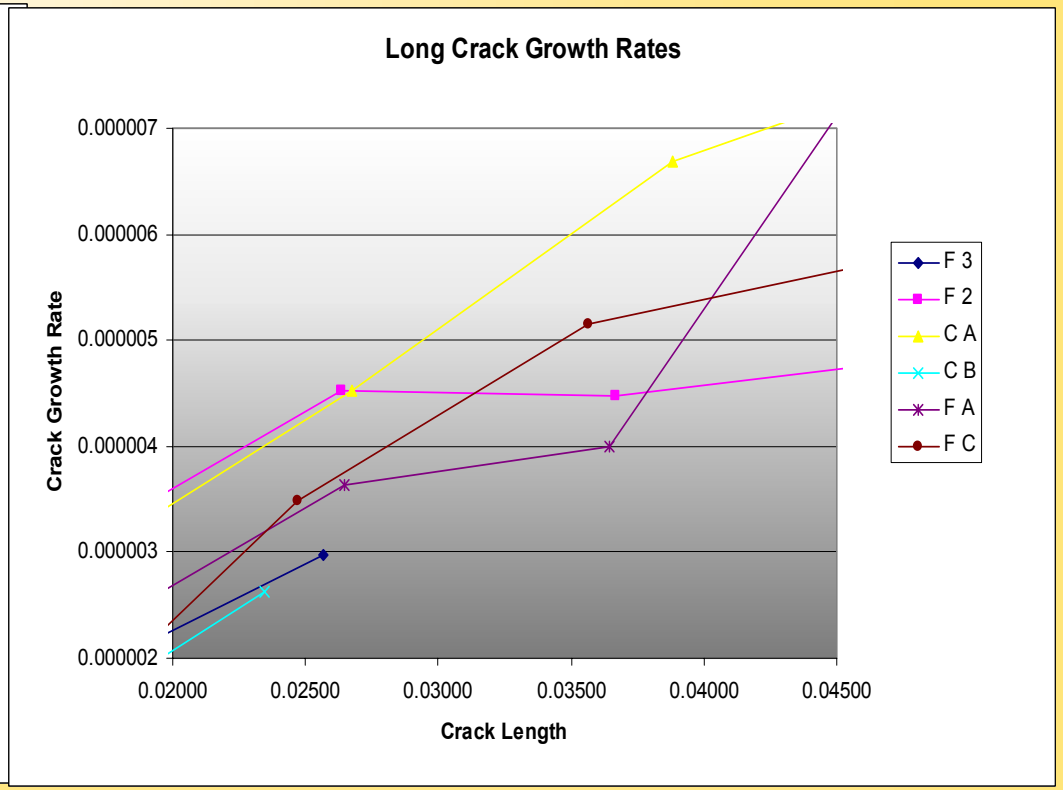
Primary cracks (Red)



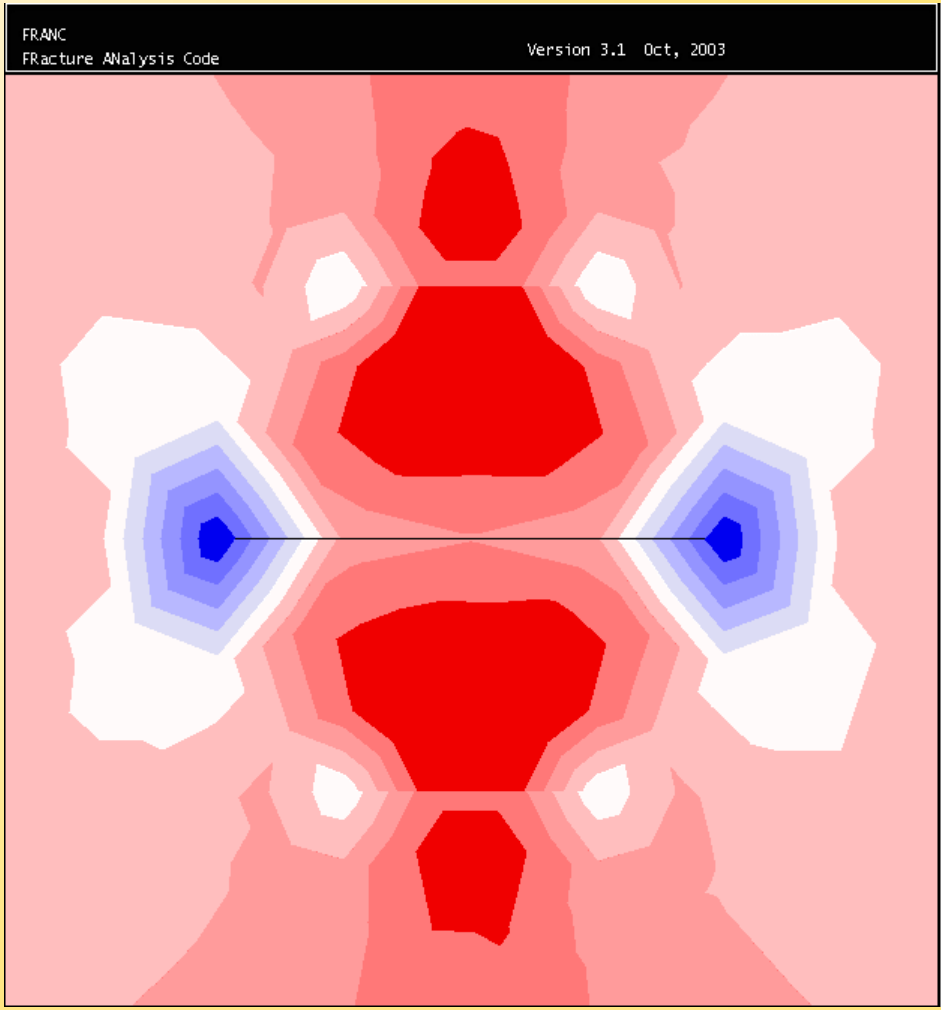
# Crack Growth Rate Data

## Growth Rates of Primary Cracks



# Illustrative Crack Shielding FEM


$K_I$=1.872, 1.455

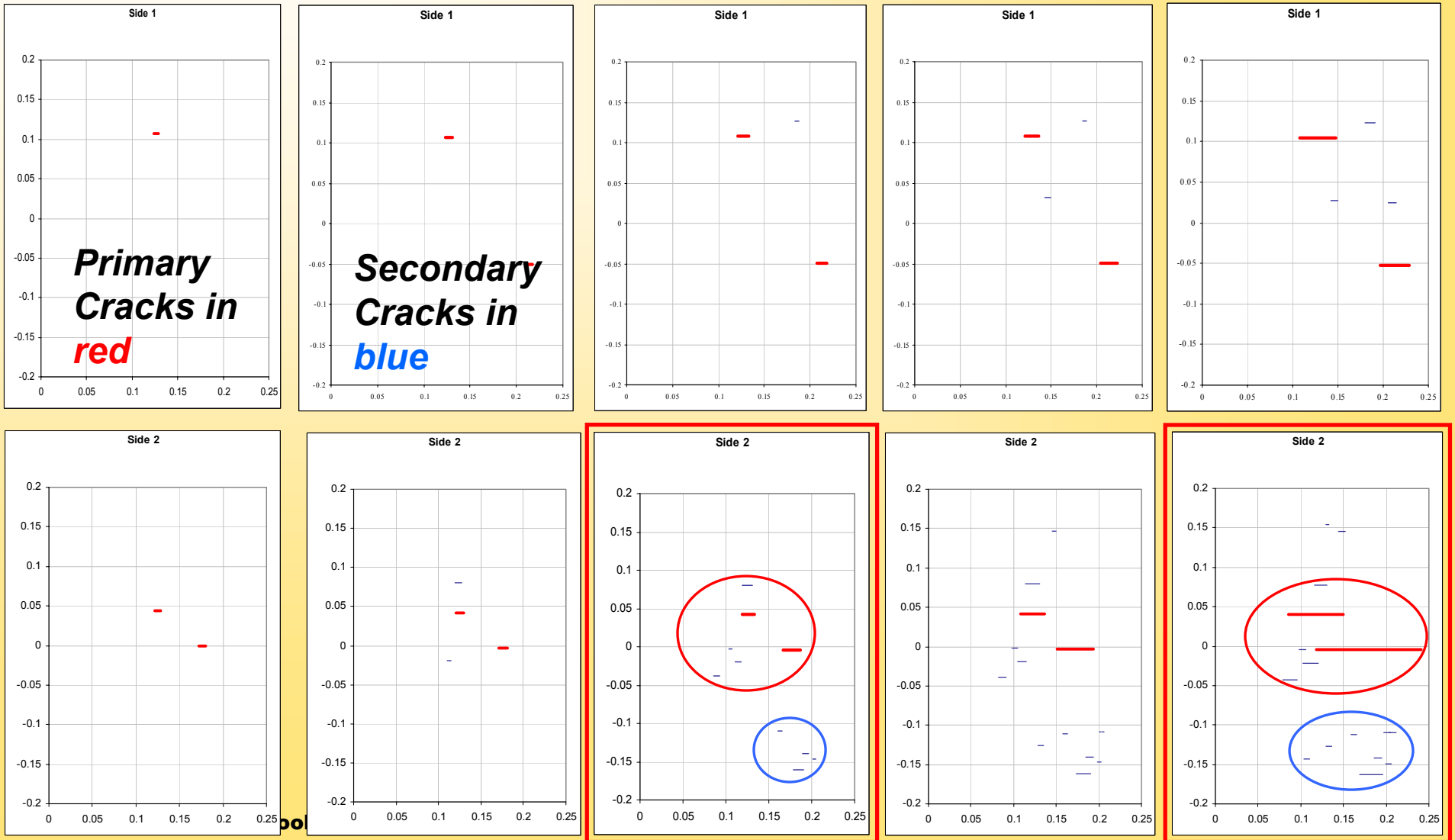
$K_I$=1.913, .7129



*Performed on Franc 2d (Cornell University)

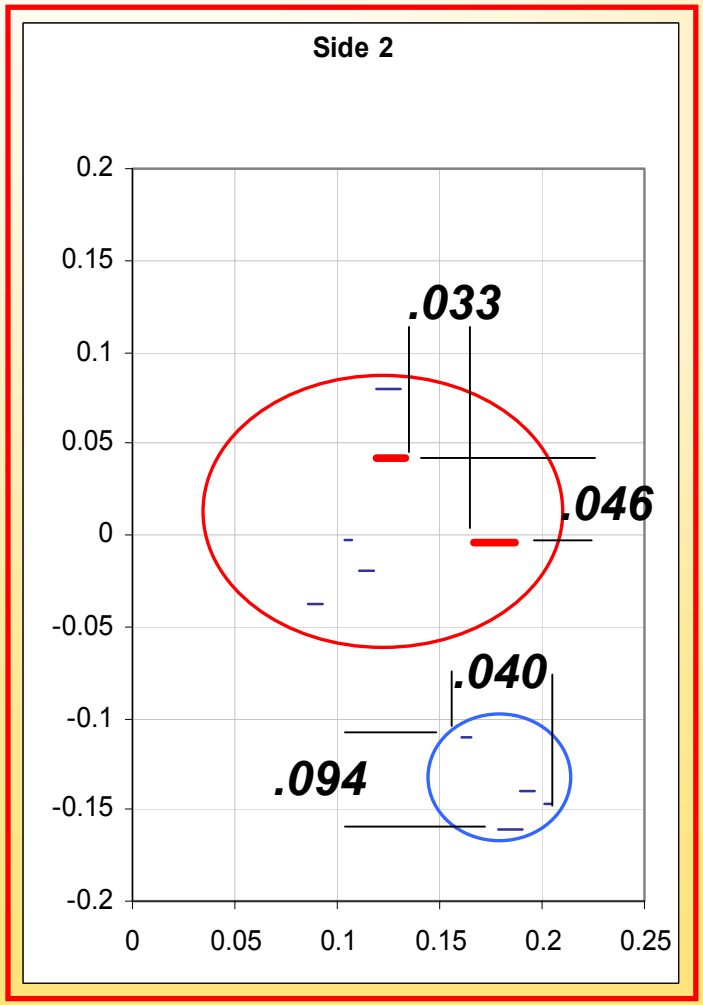
# Evolution of Clusters

| 40,000 Cycles | 45,000 Cycles | 50,000 Cycles | 55,000 Cycles | 60,000 Cycles |
|---|---|---|---|---|

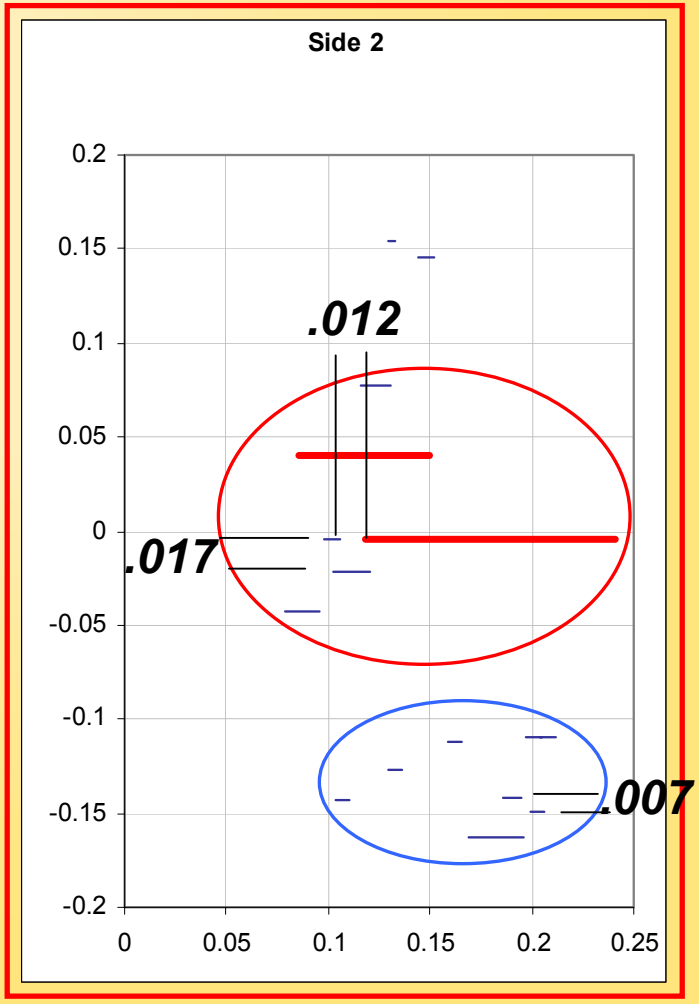


# Evolution of Clusters

*50,000 Cycles*

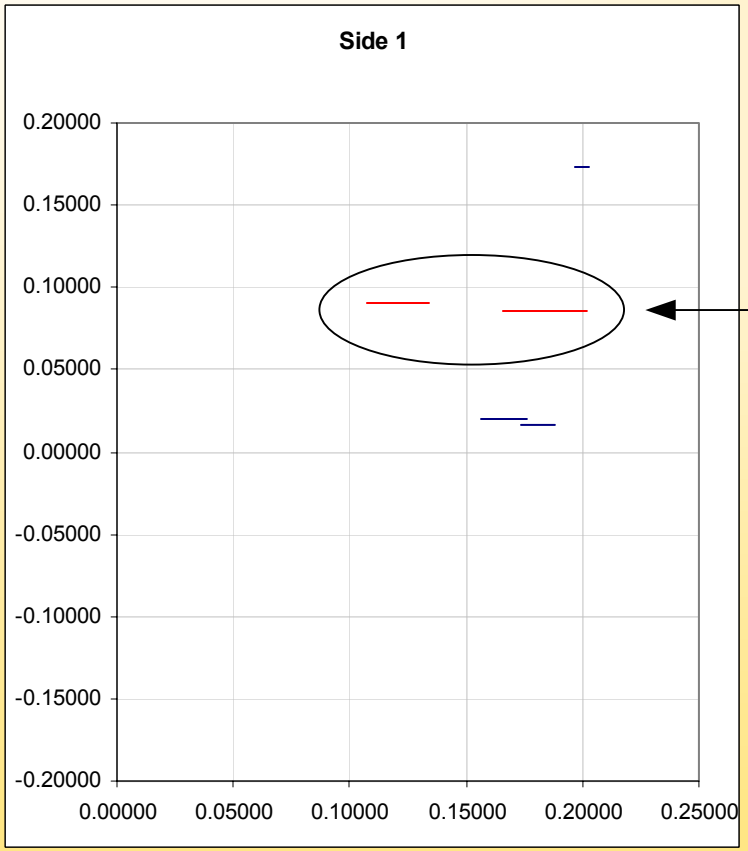



*60,000 Cycles*

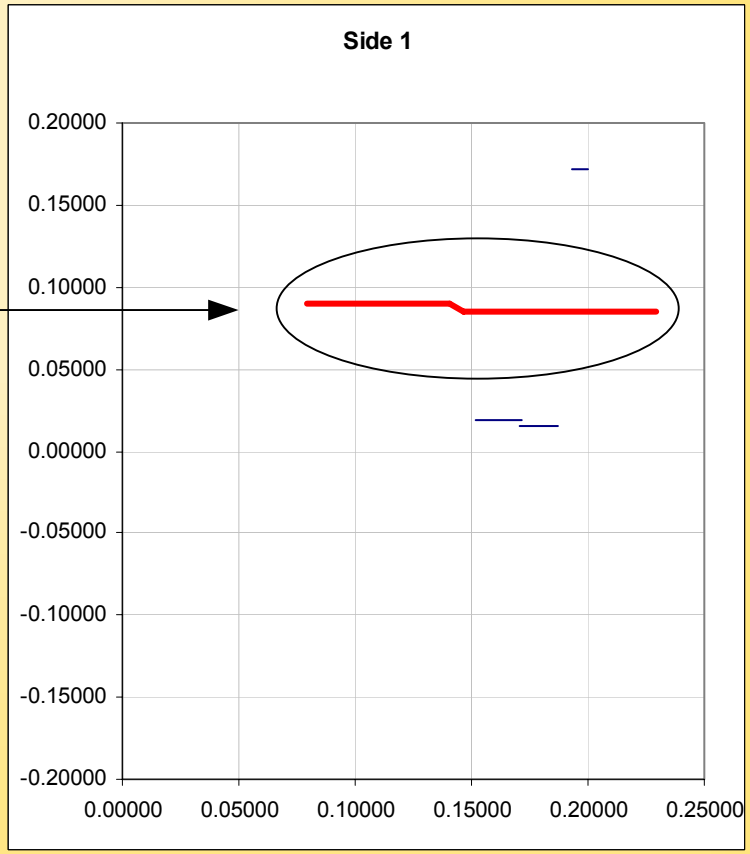


# Evolution of Clusters

*52,500 Cycles*

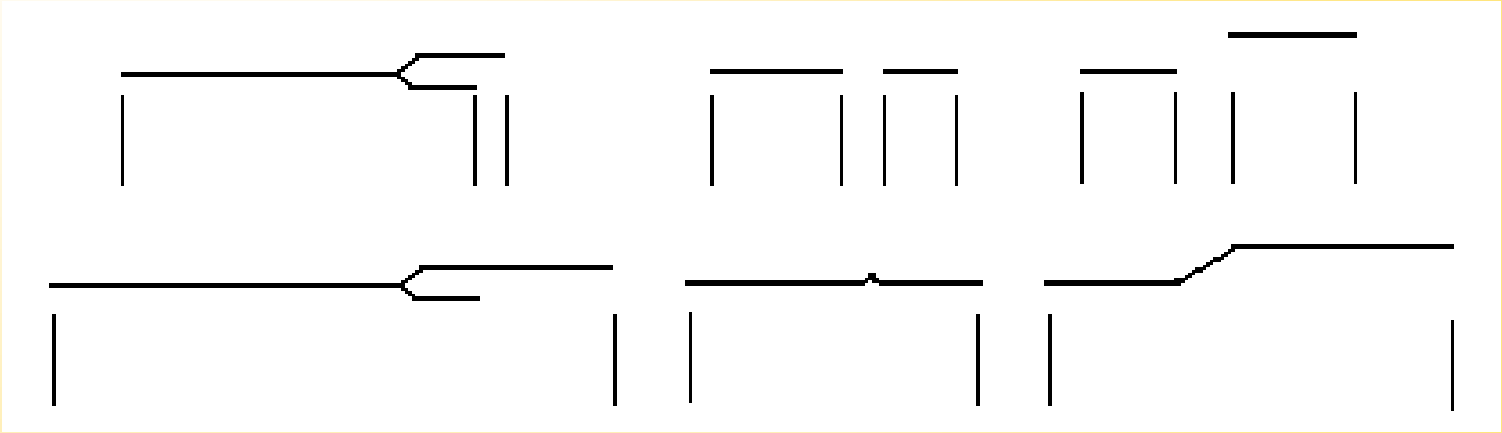



*57,500 Cycles*



# Crack Morphology

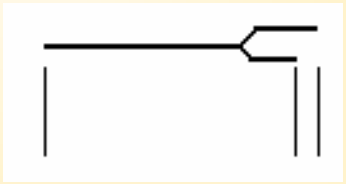
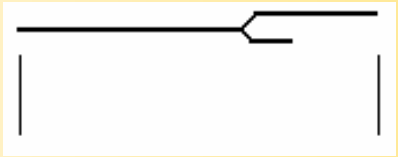
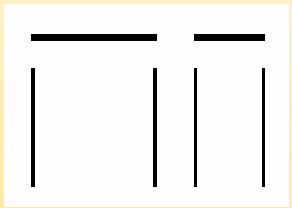
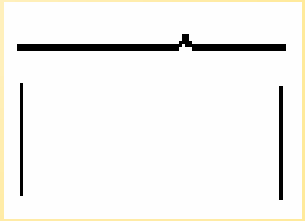
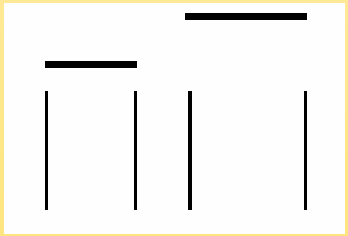
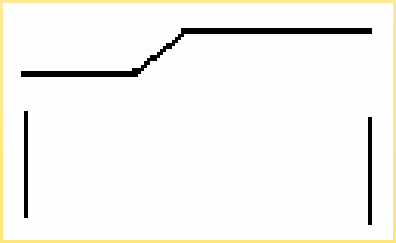
## Examples of Observed Crack Patterns



- *Many cracks will have complex shapes*
- *Long crack behavior must be observed to assign proper length*

# Crack Morphology

## Examples of Observed Crack Patterns

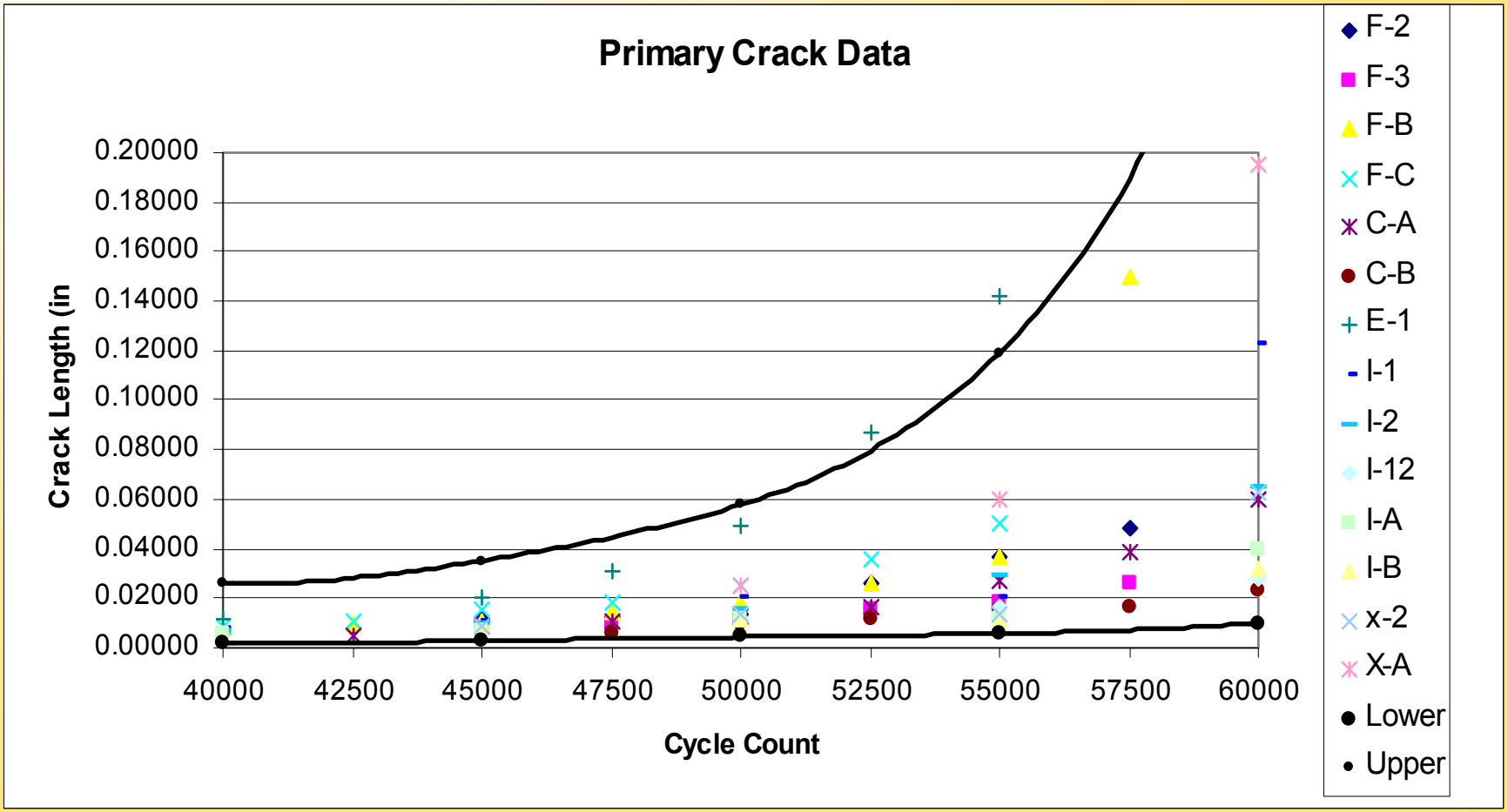
| Name | Stage 1 | Stage 2 | Explanation |
|---|---|---|---|
| ***Forked Crack*** |  |  | •One fork arrests, one grows.<br>•Length is length to longer fork. |
| ***Kinked Crack*** |  |  | • Formed through coalescence.<br>•Tabulated as one crack after coalescence. |
| ***Stepped Crack*** |  |  | •Formed through coalescence, which does not always occur.<br>•Tabulated as one crack after coalescence. |

# Analysis

- *Lognormal distribution assumed for crack lengths at each cycle count.*
- *Student-t analysis performed to calculate 95% confidence bounds.*
- *This procedure can be used to bound small crack growth until $a_{cr}$, where normal methods of crack growth analysis can be used.*
- *This allows calculation of the 95% confidence limit on failure time.*

# Analysis Example

## Confidence Bounds on Primary Crack Growth



# *Objectives of Continuing Research*

- *Extend the Bi-Modal statistical representation of small cracks.*
- *Similar to EIFS methodology however it seeks a physically based approach to include the entire small crack regime.*
- *Issues to be resolved:*
  - *Stress level/Load ratio (R) effects.*

# Objectives of Continuing Research

- *Operational Condition Issues*

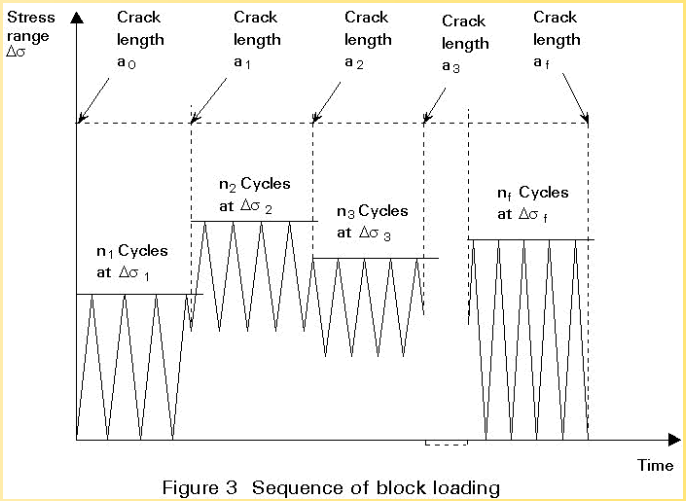
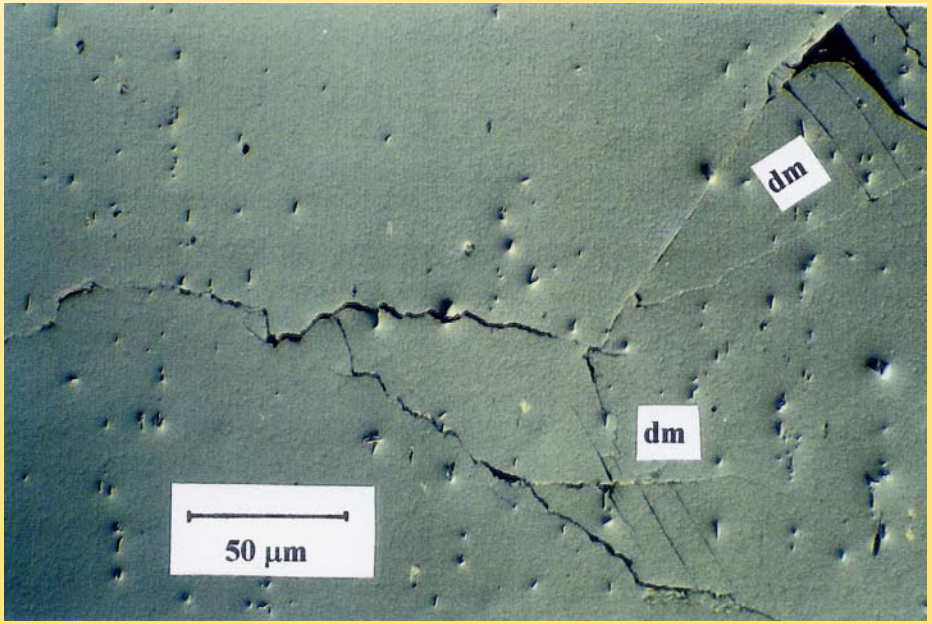


Figure 3 Sequence of block loading

  - *Variable amplitude loading, overload/underload effects.*
  - *Material orientation effects (ex. Plate, rod…)*
  - *Surface preparation effects.*

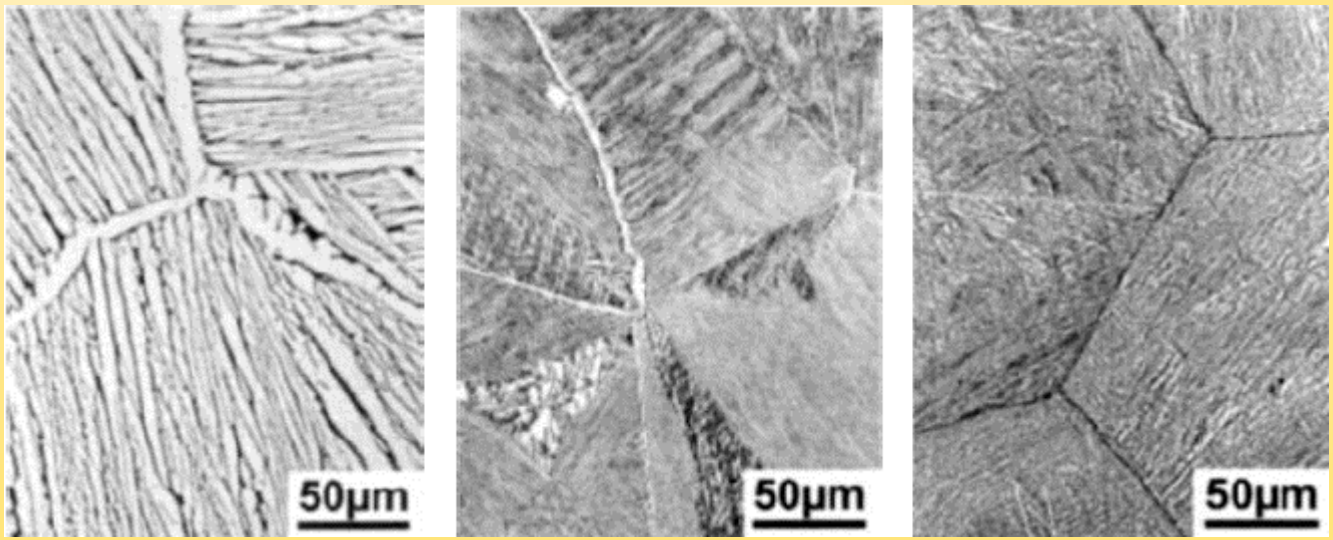
# Objectives of Continuing Research

- *Analysis:*
  - *Crack shielding in random cluster effects.*
  - *Use of statistically based, effective stress intensity factor incorporating above mentioned physical effects.*



# Objectives of Continuing Research

- *Additional Materials (β-Annealed Ti-6Al-4V):*
  - *Dual Phase, Widmänsatten/Colony Microstructure*
    - *α (HCP), β (BCC)*
  - *Key Parameters: Prior β grain size, α Colony Size, Width of α Lamellae*



# Contact Information/ Questions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- *Robert Carlson*
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  - *404-894-8198*

**School of Aerospace Engineering**
**Georgia Institute of Technology**
**Atlanta, GA, USA**

# Questar

- *Questar QM1 Telemicroscope*
- *≈ 125 x magnification*
- *Better than 3μ resolution*
- *Capable of VHS recording*